LITHOGRAPHY FREE SELF-RECONFIGURABLE POST-RELEASE STRESS ENGINEERING FOR FIELD-PROGRAMMABLE MICROSTRESSBOTS

Ratul Majumdar¹ and Igor Paprotny^{1*}

¹University of Illinois at Chicago, Chicago, USA

ABSTRACT

Stress Engineering is a method that induces curvature in initially planar micromachined structures by deposition of a stressor layer. Post-release stress engineering occurs when the stressor layer is deposited and patterned *after* the release of the underlying microstructures. In this paper we present a post-release stress engineering process which patterns the stressor layer without the use of a photolithography step through a set of *in-situ* fabricated reconfigurable shadow masks. These shadow masks are made by the same surface micromachining fabrication process as the stress-engineered structures, and their self-reconfiguration enables precise definition of the evaporated stressor layer. The alignment of the masks is automated using surface-micromachined actuators called scratch drive Actuators (SDAs) which move the shadow masks to the desired configuration. We present both theoretical and experimental results showing the viability of the new post-release stress-engineering method. In particular, application of self-reconfigurable shadow masks to developing a suite of field-programmable MicroStressBots (i.e. MicroStressBots where the steering arms can be programmed after most of the micromachining process) is presented.

INTRODUCTION

Post-release stress-engineering using *in-situ* fabricated shadow masks was first introduced in [1] to eliminate stressor (Chromium (Cr)) layer photolithography and inherent possibility of galvanic attack. In this paper we extend the concept of post-release stress engineering to present novel designs of self-actuated reconfigurable shadow masks that automatically pattern the stressor layer, and hence program, the stress engineered MEMS microrobots (MicroStressBots) [2]. The shadow-masks are actuated using built-in tethered scratch drive actuators (SDAs), which control the level of coverage during the stress engineering process, and hence the deflection of the steering arms of the MicroStressBots. We envision a miniature portable PVD chamber that can be used to program a set of initially planar microrobots, allowing for simple in-the-field (i.e. after the fabrication process) programming of MicroStressBots prior to their deployment.

The self-reconfigurable shadow masks allows for programming of MicroStressBots [2] by customizing the coverage of the stressor layer (Cr) on the steering arms. The variations in Cr-coverage in turn leads to differences in snap-down and release voltages, and thus different trajectories of motion for the individual robots. Consequently, self-reconfigurable stress engineering can thus enable simultaneous control of multiple MEMS microrobots.

RELATED WORK

The past decade has seen the development of several microscale mobile robotic systems, e.g. electrostatically driven stress-engineered micro robots (MicroStressBots) [2], resonating stepping robots [3], stick-slip magnetic walkers [4], and micro screw-based swimmers[5].

Stress engineering is a crucial part for programing the behavior of independently controlled microrobots [6]. The Stoney's equation first reported in [7] studies the effect of thin metallic films on underlying microstructures. The theory has been modified to include the effect on microcantilevers in [8]. Judy *et. al.* [9] has also reported deflection of microstructures due to deposition of thin film layer. Previous work on stress engineering [7, 8] takes into account only pre-release stressor layer deposition. However, post-release stress engineering which removes the photolithography steps and the effects of galvanic attack was first described in Majumdar *et. al.* [1]. This paper extends this work by introducing self-patterning of the evaporated metallic stressor layer by selective shadow masking propelled using in-situ fabricated scratch drive actuators (SDAs).

Simultaneous independent control of multiple microrobots on the same homogenous operating environment is a challenging task. Donald *et. al.* [10] showed that this is a highly under actuated control problem, and for a planar system can be viewed as a path matching problem which can be solved using Global Control Selective Response (GCSR) [6].

MICROSTRESSBOTS

The stress-engineered MEMS microrobot (MicroStressBot for short) consists of an untethered scratch drive actuator (USDA) [11] that provides forward motion and a curved steering-arm actuator that determines whether the robot moves straight or turns. Fig. 1 shows a kinematic view of a MicroStressBot. The steering-arm actuator consists of a long cantilever beam with a circular pad and a dimple to prevent irreversible stiction. Independent parallel control of many such microrobots can be facilitated by the process of stress engineering which enables varying coverage of stressor layer deposition on MicroStressBot [2] arms and hence individually changing the snap-down and release voltages of each microrobot.

Figure 1: Kinematics of MicroStressBots.

POST RELEASE STRESS ENGINEERING

Post release stress engineering requires patterning of an evaporated stressor layer (in this case Chromium) covered by *in-situ* shadow masks *after* the HF release. Hence, this process requires taking into account the gradual deflection of the test structures during the course of stressor deposition. The modelling can be performed numerically with the following equations as shown in [1],

$$d(j, i) = \rho(j, i-1) - \rho(j, i-1) \cos(iL/b\rho(j, i-1)) \quad (I)$$

$$\rho(j, i) = \frac{6E_1 h_1^2 E_2 h_2^2(j, i) + (4E_1 h_1^3 E_2 + 3E_1 E_2 h_1^3) h_2(j, i) + E_1^2 h_1^4}{6h_1 h_2^2(j, i) E_1 \sigma_{mi} + 6h_1^2 E_1 h_2(j, i) \sigma_{mi}} \quad (II)$$

$$h_2(j+1,i) = h_2(j,i) + (Cr \cos(\theta(j,i))), \quad (\text{III})$$

where for each time step j and for each segment on the cantilever i the deflection $d(j,i)$, radius of curvature $\rho(j,i)$ and Cr thickness $h_2(j,i)$ are iteratively calculated.

The MicroStressBots along with the reconfigurable *in-situ* shadow masks are fabricated by surface micromachining in a third party foundry process [12]. It consists of three mechanically independent layers of polycrystalline silicon with two oxide layers in between. As the shadow masks itself is not resistant to bending during Cr deposition, stress-resistant structures can be attached separately which prevents the shadow masks from bending. Different cantilever cross-section designs have been developed to resist bending during blanket stressor evaporation. Fig. 2 illustrates the different radius of curvature for three (a-c) type cross section, while Tab. I shows the design of microstructure (a) has the largest radius of curvature and hence minimum deflection which is the main requirement of a stress-resistant structure.

Figure 2: Cantilevers (a)-(c) with different cross sections.

Table I: Different designs of stress-resistant structures with cross sections and respective radii of curvature

(a)		$r=13.7 \text{ mm}$
(b)		$r=8.5 \text{ mm}$
(c)		$r=4.9 \text{ mm}$

SELF-RECONFIGURABLE SHADOW MASKS

Scratch Drive Actuators (SDAs) have been traditionally used as linear electrostatic actuators [13]. We employ microfabricated SDAs with movable *in-situ* shadow masks to provide reconfigurability of the final stressor layer deposition. Fig. 4 shows a twelve SDA linear actuator used to selectively cover four cantilevers from stressor layer deposition. The shadow masks and the cantilevers are made of surface micromachined polysilicon layers. The support beams are made of stress-resistant structures described in Tab. I to prevent the entire structure from bending during the stressor deposition. After the deposition process, the shadow masks were manually retracted in Fig. 4(iv) and the deflections of the cantilever beams were measured.

Figure 4: Sequence (i)-(iv) showing the shadow masks sliding over a cantilever test structures before stressor layer deposition (i-iii), and after deposition of 75nm Cr(iv).

Two separate runs of 75nm Cr stressor deposition were performed on the same test structures with similar shadow masks but of different lengths of exposed parts. The profilometric data thus obtained and shown in Fig. 5 clearly reveals the change in deflection of the same test structures with varying lengths of coverage due to the reconfigurable shadow masks.

Figure 5: Profilometric data of two test structures (a), (b) in two different runs having different Cr coverage area (deposition thickness: 75nm). The red and blue dotted lines demarcates the exposed and unexposed parts of the test structures.

Self-reconfigurable shadow mask shown in Fig. 6 has been implemented to pattern the steering arms of MicroStressBots. The shadow masks consist of a long stress-resistant beam attached to five SDAs on each side. Symmetry has been followed through the whole structure to provide equal force from each side. The beam itself is connected with the main shadow mask on one end and a retractable spring on the other. Similar to the previous design, both the MicroStressBots [2] which are used as test structures and the shadow mask are made of polycrystalline silicon layers.

Figure 6: Sequence of micrographs (i), (ii) and (iii) showing the motion of shadow masks over the MicroStressBots. Inset shows patterning of steering arms.

Optical micrographs taken before and after the Cr deposition in Fig. 7 reveals minor deflection of the shadow mask that did not affect the stressor evaporation on the steering arm.

Figure 7: (left) Self-reconfigurable shadow mask and MicroStressBots before and (right) after Cr deposition of 75nm.

Similar profilometric analysis on the MicroStressBot [2] arms were performed based on single run of 75nm Cr deposition but with different exposed areas. Fig. 8 shows that the difference in deflection of the two arms resulted from the process due to variable Cr coverage.

Figure 8: Optical profilometry data of the steering arm of MicroStressBots with different areas of Cr deposition coverage

FIELD-PROGRAMMABLE MICROSTRESSBOTS

The reconfigurable shadow masks designed in this work allow lithography-free self-reconfigurable patterning of the stressor layer over the MicroStressBot chassis thus ensuring proper programming of the individual devices. In order to enable field-programming of the MicroStressBots, a small evaporation chamber can be envisioned. The shadow masks will define the area of Cr

deposition dependent on the desired programming of the steering arms. This would in turn ensure independent control during multi-microrobot actuation [6].

It is also important to ensure that the backplate of the SDA is protected from stressor deposition. This is important, as blanket chrome deposition on the entire microrobot results in deformed back plate and erratic microrobot actuation. Optical profilometry of two microrobots in Fig. 9 with patterned Cr deposition with reconfigurable shadow masks (bottom) and blank Cr deposition (top).

Figure 9: (top) Backplate of MicroStressBot curved due to blanket Cr deposition. (bottom) Backplate unaffected due to patterned Cr deposition.

The two microrobots shown in Fig. 2 were placed side by side and tested on an operating environment consisting of a set of insulated parallel interdigitated electrodes. Our experiments confirmed that the MicroStressBot that experienced blanket Cr deposition is unable to move compared with the shadowed device.

Figure 10: Difference in motion of two microrobots on the operating environment. (left) Microrobot with patterned Cr deposition moves as expected whereas (right) microrobot with blanket Cr deposition does not move.

The snap-down and release voltages of each microrobot are among other dictated by the area exposed to the stressor (Cr) deposition on steering arm. The self-reconfigurable shadow masks allow us to vary the Cr deposition without the use of lithography, or any processing steps prior to stressor evaporation. The post-release stress-engineered MicroStressBots were then tested for their two degrees of motion, translation and rotation as given in Fig. 11.

Figure 11: Composite optical micrograph of a MicroStressBot with patterned Cr deposition showing two degrees of motion.

Fig. 12 shows the two control primitives which were used to actuate the robot in Fig. 11. The use of in-situ reconfigurable shadow masks allowed us to program the robot with the respective snap-down and release voltages.

Figure 12: Control primitives for a single MicroStressBot having two degrees of motion

CONCLUSION

We presented a post-release stress-engineering process for MicroStressBots using *in-situ* fabricated reconfigurable shadow masks, and applied this process to several different structures including the steering-arms of stress-engineered MEMS microrobots. We showed designs of shadow masks that can be reconfigured using Scratch Drive Actuators (SDAs) prior to the deposition of the stressor layer. This enables precise definition of the curvature of steering-arms of the MicroStressBots without the need for an additional photolithography steps, greatly simplifying the fabrication process. The presented process not only avoids potential galvanic attack during final release etch of the MEMS structures but also is highly compatible with die-level post processing of devices fabricated using multi-project wafer processes [12]. Moreover, the presented post-release stress-engineering process was applied to define the deflections of steering arm of several MicroStressBots which in turn helps in multi robot control mechanism. The shadow masks can be configured to cover different parts of the steering arms thus fabricating multiple microrobots of varying motion simultaneously. The reconfiguration of the shadow-masks using *in-situ* fabricated actuators allow precise definition of curvature of planar MicroStressBots by the use of a simple small PVD chamber, and is envisioned to be used on-site (in the field) prior to the deployment of the fabricated MicroStressBots. Such capability is envisioned to have big potential to enable parallel control of large numbers of MicroStressBots.

ACKNOWLEDGEMENTS

This project was funded in part from a grant by the College of Engineering, University of Illinois at Chicago, Chicago, IL. Travel support has been generously provided by the Transducer Research Foundation.

REFERENCES

- [1] R. Majumdar, Vahid Foroutan, and Igor Paprotny, "Post-release stress-engineering of surface-micromachined MEMS structures using evaporated Chromium and in-situ fabricated reconfigurable shadow masks." In Micro Electro Mechanical Systems (MEMS), 2015 28th IEEE International Conference on, pp. 296-299. IEEE, 2015.
- [2] B. R. Donald, C. Levey, C. McGray, I. Paprotny, and D. Rus. "An Untethered, Electrostatic, Globally-Controllable MEMS Micro-Robot", Journal of Microelectromechanical Systems (J.MEMS), 2006; 15(1):1-15.
- [3] D.R. Frutiger, B.E. Kratochvil, K. Vollmers, B.J. Nelson, "Magmites wireless resonant magnetic microrobots," Proceedings of IEEE International Conference on Robotics and Automation (ICRA), May 2008.
- [4] S. Floyd, C. Pawashe, and M. Sitti, "An untethered magnetically actuated micro-robot capable of motion on arbitrary surfaces", Proceedings of IEEE International Conference on Robotics and Automation (ICRA), May, 2008.
- [5] A. Ghosh and P. Fischer, "Controlled propulsion of artificial magnetic nanostructured propellers", Nano letters, vol. 9, issue 6, pp. 2243–2245, 2009.
- [6] B.R. Donald, C.G. Levy, I. Paprotny, D. Rus, "Planning and control for microassembly of structures composed of stress-engineered MEMS microrobots," International Journal of Robotics Research, vol. 32, no. 2, pp. 218-246, 2013.
- [7] G. G. Stoney, "The tension of metallic films deposited by electrolysis," Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, vol. 82, no. 553, pp. 172–175, 1909.
- [8] C.-L. Tsai and A. K. Henning, "Out-of-plane microstructures using stress engineering of thin films," in Micromachining and Microfabrication. International Society for Optics and Photonics, 1995, pp. 124–132.
- [9] M. W. Judy, Y.-H. Cho, R. T. Howe, and A. P. Pisano, "Self-adjusting microstructures (sams)," in Micro Electro Mechanical Systems, 1991, MEMS'91, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE. IEEE, 1991, pp. 51–56.
- [10] B.R. Donald, C.G. Levey, I. Paprotny and D. Rus, "Simultaneous control of multiple MEMS microrobots," 9th international workshop on algorithmic foundations of robotics(WAFR), Guanajuato, Mexico, Dec. 7-9, 2008, pp. 69-84, Berlin:Springer-Verlag.
- [11] B.R. Donald, C.G. Levey, C. McGray, D. Rus and M. Sinclair, "Power delivery and locomotion of untethered microactuators", Journal of Microelectromechanical Systems, vol. 10 issue 6, pp. 947-959, 2003.
- [12] D. Koester, A. Cowen, R. Mahadevan, M. Stonefield, and B. Hardy, PolyMUMPs Design Handbook, A MUMPs Process, 10th ed. Grenoble, France: MEMSCAP, 2003.
- [13] T. Akiyama and H. Fujita, "A quantitative analysis of scratch drive actuator using buckling motion," in IEEE Proc. Int. Conf. Micro Electro Mechanical Systems, 1995, pp. 310–315.

CONTACT

*I.Paprotny, tel: +1(312)996-1924;paprotny@uic.edu